CP VIOLATION IN $B^0 \to \pi^+\pi^-$ DECAY

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We present an improved measurement of CP-violating asymmetries in $B^0 \to \pi^+\pi^-$ decays based on a 78 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We reconstruct one neutral B meson as a $B^0 \to \pi^+\pi^-$ CP eigenstate and identify the flavor of the accompanying B meson from its decay products. From the asymmetry in the distribution of the time intervals between the two B meson decay points, we obtain the CP-violating asymmetry amplitudes $\mathcal{A}_{\pi\pi} = +0.77 \pm 0.27(\text{stat}) \pm 0.08(\text{syst})$ and $\mathcal{S}_{\pi\pi} = -1.23 \pm 0.41(\text{stat}) {}^{+0.08}_{-0.07}(\text{syst})$, where the statistical uncertainties are determined from Monte Carlo pseudo-experiments. We rule out the CP-conserving case, $\mathcal{A}_{\pi\pi} = \mathcal{S}_{\pi\pi} = 0$, at the 99.93% confidence level. We discuss how these results constrain the value of the CKM angle ϕ_2.

1 INTRODUCTION

Kobayashi and Maskawa (KM) proposed, in 1973, a model where CP violation is incorporated as an irreducible complex phase in the weak-interaction quark mixing matrix [1]. The KM model predicts CP-violating asymmetries in the time-dependent rates for B^0 and $\overline{B}^0$ decays to a common CP eigenstate, f_{CP}, as

$$A_{CP}(t) \equiv \frac{\Gamma(\overline{B}^0 \to f_{CP};t) - \Gamma(B^0 \to f_{CP};t)}{\Gamma(\overline{B}^0 \to f_{CP};t) + \Gamma(B^0 \to f_{CP};t)} = A_f \cos(\Delta m_d t) + S_f \sin(\Delta m_d t), \tag{1}$$

where $\Gamma(B^0 \to f_{CP};t)(\Gamma(\overline{B}^0 \to f_{CP};t))$ is the partial decay rate of pure $B^0(\overline{B}^0)$ state at $t = 0$, and Δm_d is the mass difference between the two B^0 mass eigenstates [2]. The CP-violating parameters A_f and S_f defined in Eq. (1) are expressed by $A_f = (|\lambda_f|^2 - 1)/(|\lambda_f|^2 + 1)$ and $S_f = 2Im\lambda_f/(|\lambda_f|^2 + 1)$, where λ_f is a complex parameter that depends on $B^0\overline{B}^0$ mixing,

on CP eigenvalue of f_{CP} and on the amplitudes for B^0 and $\overline{B}^0$ decay to f_{CP}. In the mode $B^0 \to J/\psi K_S$ [3], the Standard Model predicts $S_{J/\psi K_S} = \sin 2\phi_1$ [4] and $A_{J/\psi K_S} = 0$. Recent measurements of the CP-violating parameter $\sin 2\phi_1$ by the Belle [5] and BaBar [6] collaborations established CP violation in the $b \to c\bar{c}s$ that is consistent with KM expectations. In the mode $B^0 \to \pi^+\pi^-$, we would have $\mathcal{S}_{\pi\pi} = \sin 2\phi_2$ and $\mathcal{A}_{\pi\pi} = 0$, or equivalently $|\lambda_f| = 1$, if the $b \to u$ tree amplitude were dominant. The situation is complicated by the possibility of significant contributions from gluonic $b \to d$ penguin amplitudes that have a different weak phase and additional strong phases [7]. As a result, $\mathcal{S}_{\pi\pi}$ may not be equal to $\sin 2\phi_2$ and direct CP violation, $\mathcal{A}_{\pi\pi} \neq 0$, may occur.

2 EXPERIMENTAL APPARATUS

In this paper, we report an updated measurement [8] that is based on a 78 fb^{-1} data sample, containing $85{\times}10^6$ $B\overline{B}$ pairs, which were collected with the Belle detector [9] at the KEKB asymmetric-energy e^+e^- collider [10] at Υ(4S) resonance. KEKB archives the highest peak luminosity of 8.26×10^{33}cm^{-2}s^{-1} as of March, 2003. The Belle detector is a large-solid-angle general purpose spectrometer that consists of a silicon vertex detector (SVD), a central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect K_L^0 mesons and muons.

3 EXPERIMENTAL METHOD

Experimental method in this report is very similar to the well-established $\sin 2\phi_1$ measurement [5] in $B^0 \to c\bar{c}K_S$. In the decay chain $\Upsilon(4S) \to B^0\overline{B}^0 \to f_{CP}f_{\rm tag}$, where one of B mesons decays at time t_{CP} to f_{CP} and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\overline{B}^0$, the decay rate has a time dependence given by [11]

$$\mathcal{P}^q_{\pi\pi}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 + q\cdot\{\mathcal{S}_{\pi\pi}\sin(\Delta m_d \Delta t) + \mathcal{A}_{\pi\pi}\cos(\Delta m_d \Delta t)\}\right], \tag{2}$$

where τ_{B^0} is the B^0 lifetime, $\Delta t = t_{CP} - t_{\rm tag}$, and the b-flavor charge $q = +1$ (-1) when the tagging B meson is a $B^0(\overline{B}^0)$. As described below in Section 4, we reconstruct one of B mesons with two tracks identified as pion. We determine the flavor of the accompanying B from the information of its decay products. Δt is determined from Δz, the displacement in z between the decay vertices of two B mesons: $\Delta t \simeq (z_{CP} - z_{\rm tag})/\beta\gamma c \equiv \Delta z/\beta\gamma c$, where $\beta\gamma$ is a Lorentz boost factor of 0.425. In flavor tagging and Δt measurement, we apply the same method used for the Belle $\sin 2\phi_1$ measurement [12].

The CP asymmetry parameters, $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$, are obtained from an unbinned maximum likelihood fit to the observed Δt distribution. For this purpose, we use probability density functions, P_i (PDFs) that are based on theoretical distributions given by Eq.(2). PDFs are diluted with the background and smeared by the detector response. We use the same detector response as those used for the $\sin 2\phi_1$ measurement [12,13]. In the fit, $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ are free parameters determined by maximizing the likelihood function $\mathcal{L} = \prod_i P_i$, where the product is over all $B^0 \to \pi^+\pi^-$ candidates.

4 $B^0 \to \pi^+\pi^-$ RECONSTRUCTION

The $B^0 \to \pi^+\pi^-$ event selection is described in detail elsewhere [14]. We use oppositely charged track pairs that are positively identified as pions according to the combined information from the

ACC and the CDC dE/dx measurement. The efficiency of the pion identification is 91% and the contamination from miss-identified kaon is 10% for the track momentum from 1.5 to 4.5 GeV/c. Candidate B mesons are reconstructed using the energy difference $\Delta E \equiv E_B^{\rm cms} - {E_{\rm beam}^*}^{\rm cms}$ and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{({E_{\rm beam}^*}^{\rm cms})^2 - (p_B^{\rm cms})^2}$, where ${E_{\rm beam}^*}^{\rm cms}$ is the cms beam energy, and $E_B^{\rm cms}$ and $p_B^{\rm cms}$ are the cms energy and momentum of the B candidate. The major sources of the background in $B^0 \to \pi^+\pi^-$ are $B^0 \to K^+\pi^-$ decays where kaons are misidentified as pions, and the background from the $e^+e^- \to q\overline{q}$ continuum ($q = u,\ d,\ s,\ c$).

In order to suppress the continuum background, we form signal and background likelihood functions, $\mathcal{L}_S$ and $\mathcal{L}_{BG}$, from two variables. One is a Fisher discriminant determined from six modified Fox-Wolfram moments [15]; the other is the cms B flight direction with respect to the z axis. We determine $\mathcal{L}_S$ from a GEANT-based Monte Carlo (MC) simulation [16], and $\mathcal{L}_{BG}$ from ΔE-$M_{\rm bc}$ sideband data dominated by the continuum background. We reduce the continuum background by imposing requirements on the likelihood ratio $LR = \mathcal{L}_S/(\mathcal{L}_S+\mathcal{L}_{BG})$ for candidate events. We optimize LR requirement for each flavor tagging category to maximize the expected sensitivity.

5 SIGNAL YIELD

Figures 1(a) and (b) show the ΔE distributions for the $B^0 \to \pi^+\pi^-$ candidates that are in the $M_{\rm bc}$ signal region with $LR > 0.825$ and with $LR \leq 0.825$, respectively, after flavor tagging and vertex reconstruction. In the $M_{\rm bc}$ and ΔE signal region, we find 275 candidates for $LR > 0.825$ and 485 candidates for $LR \leq 0.825$. The $B^0 \to \pi^+\pi^-$ signal yield for $LR > 0.825$ is extracted by fitting the ΔE distribution with a Gaussian signal function plus contributions from misidentified $B^0 \to K^+\pi^-$ events, three-body B-decays, and continuum background. The fit yields 106^{+16}_{-15} $\pi^+\pi^-$ events, 41^{+10}_{-9} $K^+\pi^-$ events and 128^{+5}_{-6} continuum events in the signal region. The errors do not include systematic uncertainties unless otherwise stated. Here the error on the yield of continuum events in the signal region is obtained by scaling the error of the yield from the fit that encompasses the entire ΔE range. For $LR \leq 0.825$, we fix the level of $\pi^+\pi^-$ signal by scaling the $LR > 0.825$ number by a MC-determined factor and that of the continuum background from the sideband. The ratio of the $K^+\pi^-$ background to the $\pi^+\pi^-$ signal is fixed to the value measured with the $LR > 0.825$ sample. We obtain 57 ± 8 $\pi^+\pi^-$ events, 22^{+6}_{-5} $K^+\pi^-$ events and 406 ± 17 continuum events in the signal region for $LR \leq 0.825$. The contribution from three-body B-decays is negligibly small in the signal region.

6 FIT RESULTS

The unbinned maximum likelihood fit to the 760 $B^0 \to \pi^+\pi^-$ candidates (391 B^0- and 369 $\overline{B}^0$-tags), containing 163^{+24}_{-23} $\pi^+\pi^-$ signal events, yields

$$\mathcal{A}_{\pi\pi} = +0.77 \ \pm 0.27({\rm stat}) \ \pm 0.08({\rm syst}), \quad (3)$$

$$\mathcal{S}_{\pi\pi} = -1.23 \ \pm 0.41({\rm stat}) \ ^{+0.08}_{-0.07}({\rm syst}). \quad (4)$$

Here we quote the rms values of the MC $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ distributions as the statistical errors of our measurement, because the log-likelihood ratio curves from our data deviates from parabolic behavior and the statistical error estimation using log-likelihood ratio, $-2\ln(\mathcal{L}/\mathcal{L}_{\rm max})$, is not appropriate.

7 CROSS CHECKS

We perform a number of cross checks. We measure the B meson lifetime using the same vertex reconstruction method. In addition, we check for biases in the analysis using samples of non-CP

eigenstates, $B^0 \to K^+\pi^-$ decays, and sideband data.

We perform a B^0 lifetime measurement with the $B^0 \to \pi^+\pi^-$ candidate events that uses the same background fractions, vertex reconstruction methods, and resolution functions that are used for the CP fit. The result, $\tau_{B^0} = 1.42^{+0.14}_{-0.12}$ ps, is consistent with the world-average value [17]. We also perform measurement of B^0 lifetime and B^0-$\overline{B}^0$ mixing with the 1371 $B^0 \to K^+\pi^-$ candidate events (610 signal events), that are selected using positively identified the charged kaons. we use the same vertex reconstruction method and wrong-tag fractions as $B^0 \to \pi^+\pi^-$ and determine $\tau_{B^0} = 1.46 \pm 0.08$ ps and $\Delta m_d = 0.55^{+0.05}_{-0.07}$ ps^{-1}, which are in agreement with the world average values [17].

We also use samples of non-CP eigenstate $B^0 \to D^-\pi^+$, $D^{*-}\pi^+$ and $D^{*-}\rho^+$ decays, selected with the same event-shape criteria, to check for biases in the analysis. The combined fit to this control sample of 15321 events yields $\mathcal{A} = -0.015 \pm 0.022$ and $\mathcal{S} = 0.045 \pm 0.033$. As expected, neither mixing-induced nor direct CP-violating asymmetry is observed. A fit to the $B^0 \to K^+\pi^-$ candidates candidates yields $\mathcal{A}_{K\pi} = -0.03 \pm 0.11$, in agreement with the counting analysis mentioned above [18], and $\mathcal{S}_{K\pi} = 0.08 \pm 0.16$, which is consistent with zero. A comparison of the event yields and Δt distributions for B^0- and $\overline{B}^0$-tagged events in the sideband region reveals no significant asymmetry.

8 SIGNIFICANCE

We use the Feldman-Cousins frequentist approach [19] to determine the statistical significance of our measurement. In order to form confidence intervals, we use the $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ distributions of the results of fits to MC pseudo-experiments for various input values of $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$. The distributions incorporate possible biases at the boundary of the physical region as well as a correlation between $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$; these effects are taken into account by this method. The distributions are also smeared with Gaussian functions that account for systematic errors. Figure 3 shows the resulting two-dimensional confidence regions in the $\mathcal{A}_{\pi\pi}$ vs. $\mathcal{S}_{\pi\pi}$ plane. The case that CP symmetry is conserved, $\mathcal{A}_{\pi\pi} = \mathcal{S}_{\pi\pi} = 0$, is ruled out at the 99.93% confidence level (C.L.), equivalent to 3.4σ significance for Gaussian errors. The minimum confidence level for $\mathcal{A}_{\pi\pi} = 0$, the case of no direct CP violation, occurs at $(\mathcal{S}_{\pi\pi}, \mathcal{A}_{\pi\pi}) = (-1.0, 0.0)$ and is 97.3%, which corresponds to 2.2σ significance.

9 DISCUSSION

Using the standard definitions of weak phases ϕ_1, ϕ_2, and ϕ_3, the decay amplitudes for B^0 and $\overline{B}^0$ to $\pi^+\pi^-$ are

$$A(B^0 \to \pi^+\pi^-) = -(|T|e^{i\delta_T}e^{i\phi_3} + |P|e^{i\delta_P}), \quad (5)$$

$$A(\overline{B}^0 \to \pi^+\pi^-) = -(|T|e^{i\delta_T}e^{-i\phi_3} + |P|e^{i\delta_P}), \quad (6)$$

where T and P are the amplitudes for the tree and penguin graphs and δ_T and δ_P are their strong phases. Here we adopt the notation of Ref. [20] and use the convention in which the top-quark contributions are integrated out in the short-distance effective Hamiltonian. In addition, the unitarity relation $V_{ub}^*V_{ud} + V_{cb}^*V_{cd} = -V_{tb}^*V_{td}$ is applied. Using the above expressions and $\phi_2 = \pi - \phi_1 - \phi_3$, we determine $\lambda_{\pi\pi} \equiv e^{2i\phi_2}[1 + |P/T|e^{i(\delta+\phi_3)}]/[1 + |P/T|e^{i(\delta-\phi_3)}]$. Explicit expressions for $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ are

$$\mathcal{S}_{\pi\pi} = [\sin 2\phi_2 + 2|P/T|\sin(\phi_1 - \phi_2)\cos\delta - |P/T|^2\sin 2\phi_1]/\mathcal{R}, \quad (7)$$

$$\mathcal{A}_{\pi\pi} = -[2|P/T|\sin(\phi_2 + \phi_1)\sin\delta]/\mathcal{R}, \quad (8)$$

$$\mathcal{R} = 1 - 2|P/T|\cos\delta\cos(\phi_2 + \phi_1) + |P/T|^2, \quad (9)$$

where $\delta \equiv \delta_P - \delta_T$. We take $-180° \leq \delta \leq 180°$. When $\mathcal{A}_{\pi\pi}$ is positive and $0° < \phi_1+\phi_2 < 180°$, δ is negative. Recent theoretical estimates prefer $|P/T| \sim 0.3$ with large uncertainties [21,22,23,24]. Figures 4(a)-(e) show the regions for ϕ_2 and δ corresponding to the 68.3% C.L., 95.5% C.L. and 99.73% C.L. region of $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ (shown in Fig. 3) for representative values of $|P/T|$ and ϕ_1 [25]. Note that a value of ($\mathcal{S}_{\pi\pi}$,$\mathcal{A}_{\pi\pi}$) inside the 68.3% C.L. contour requires a value of $|P/T|$ greater than ~0.3. The allowed region is not very sensitive to variations of ϕ_1 within the errors of the measurements, as can be seen by comparing Figs. 4(a), (c) and (e). The range of ϕ_2 that corresponds to the 95.5% C.L. region of $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ in Fig. 3 is

$$78° \leq \phi_2 \leq 152°, \tag{10}$$

for $\phi_1 = 23.5°$ and $0.15 \leq |P/T| \leq 0.45$. The result is in agreement with constraints on the unitarity triangle from other measurements [26].

10 CONCLUSION

In summary, we have performed an improved measurement of CP violation parameters in $B^0 \to \pi^+\pi^-$ decays. An unbinned maximum likelihood fit to 760 $B^0 \to \pi^+\pi^-$ candidates, which contain 163^{+24}_{-23}(stat) $\pi^+\pi^-$ signal events, yields $\mathcal{A}_{\pi\pi} = +0.77 \pm 0.27(\text{stat}) \pm 0.08(\text{syst})$, and $\mathcal{S}_{\pi\pi} = -1.23 \pm 0.41(\text{stat})\ {}^{+0.08}_{-0.07}(\text{syst})$, where the statistical uncertainties are determined from MC pseudo-experiments. This result is consistent with our previous measurement [27] and supersedes it. We obtain confidence intervals for CP-violating asymmetry parameters $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ based on the Feldman-Cousins approach where we use MC pseudo-experiments to determine acceptance regions. We rule out the CP-conserving case, $\mathcal{A}_{\pi\pi} = \mathcal{S}_{\pi\pi} = 0$, at the 99.93% confidence level.

The result for $\mathcal{S}_{\pi\pi}$ indicates that mixing-induced CP violation is large, and the large $\mathcal{A}_{\pi\pi}$ term is an indication of direct CP violation in B meson decay. Constraints within the Standard Model on the CKM angle ϕ_2 and the hadronic phase difference between the tree (T) and penguin (P) amplitudes are obtained for $|P/T|$ values that are favored theoretically. We find an allowed region of ϕ_2 that is consistent with constraints on the unitarity triangle from other measurements.

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25. Using the average of recent values of $\sin2\phi_1$ from Belle [12] and BaBar [6], we obtain $\phi_1 = (23.5^{+2.4}_{-2.2})^\circ$.
26. Y. Nir, hep-ph/0208080, to appear in the proceedings of XXXI International Conference on High Energy Physics, Amsterdam, Netherlands, July 24-31, 2002.
27. Belle Collaboration, K. Abe *et al.*, *Phys. Rev. Lett.* **89**, 071801 (2002). $\mathcal{S}_{\pi\pi} = -1.21^{+0.38}_{-0.27}(\mathrm{stat})^{+0.16}_{-0.13}(\mathrm{syst})$ and $\mathcal{A}_{\pi\pi} = +0.94^{+0.25}_{-0.31}(\mathrm{stat})\pm0.09(\mathrm{syst})$. In this paper, the statistical uncertainties were determined from the observed fitting errors rather than from MC pseudo-experiments as in the analysis described here. Thus, the errors here are larger than those obtained by scaling the previous errors by the integrated luminosities.

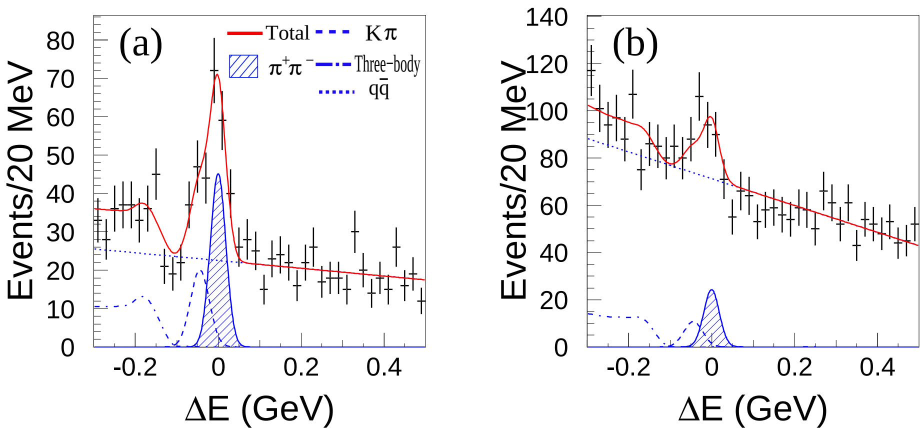

Figure 1: ΔE distributions in the $M_{\rm bc}$ signal region for (a) $B^0 \to \pi^+\pi^-$ candidates with $LR > 0.825$ and (b) $B^0 \to \pi^+\pi^-$ candidates with $LR \leq 0.825$. The sum of the signal and background functions is shown as a solid curve. The solid curve with hatched area represents the $\pi^+\pi^-$ component, the dashed curve represents the $K^+\pi^-$ component, the dotted curve represents the continuum background, and the dot-dashed curve represents the charmless three-body B decay background component.

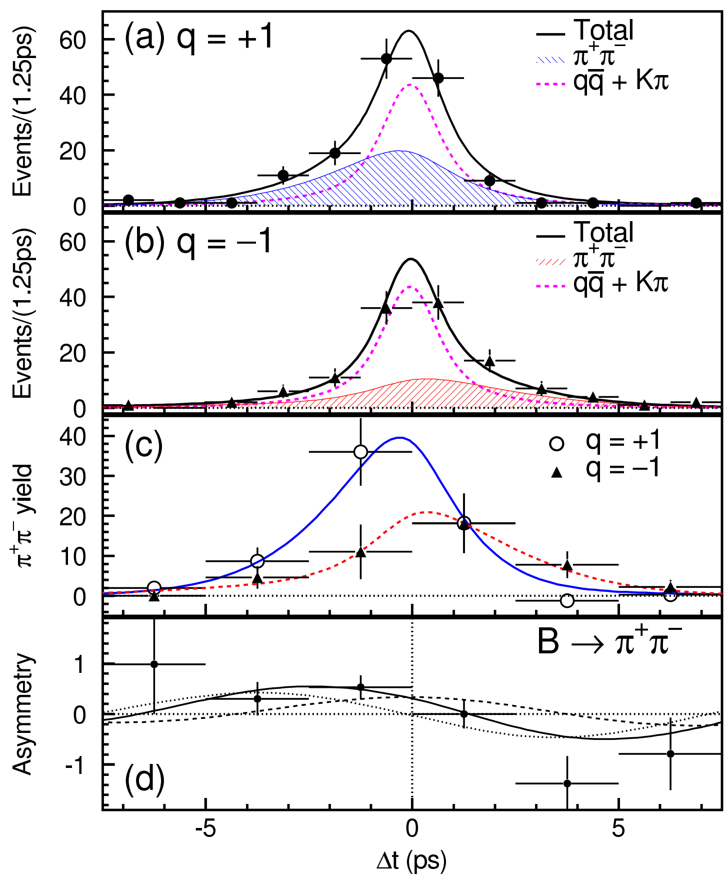

Figure 2: The raw, unweighted Δt distributions for the 275 $B^0 \to \pi^+\pi^-$ candidates with $LR > 0.825$ in the signal region: (a) 148 candidates with $q = +1$, i.e. the tag side is identified as B^0; (b) 127 candidates with $q = -1$; (c) $B^0 \to \pi^+\pi^-$ yields after background subtraction. The errors are statistical only and do not include the error on the background subtraction; (d) the CP asymmetry for $B^0 \to \pi^+\pi^-$ after background subtraction. In Figs. (a) through (c), the curves show the results of the unbinned maximum likelihood fit to the Δt distributions of the 760 $B^0 \to \pi^+\pi^-$ candidates. In Fig. (d), the solid curve shows the resultant CP asymmetry, while the dashed (dotted) curve is the contribution from the cosine (sine) term.

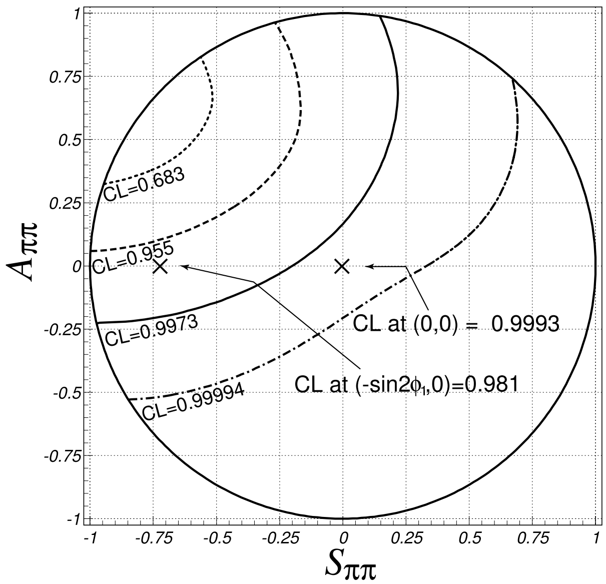

Figure 3: Confidence regions for $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$.

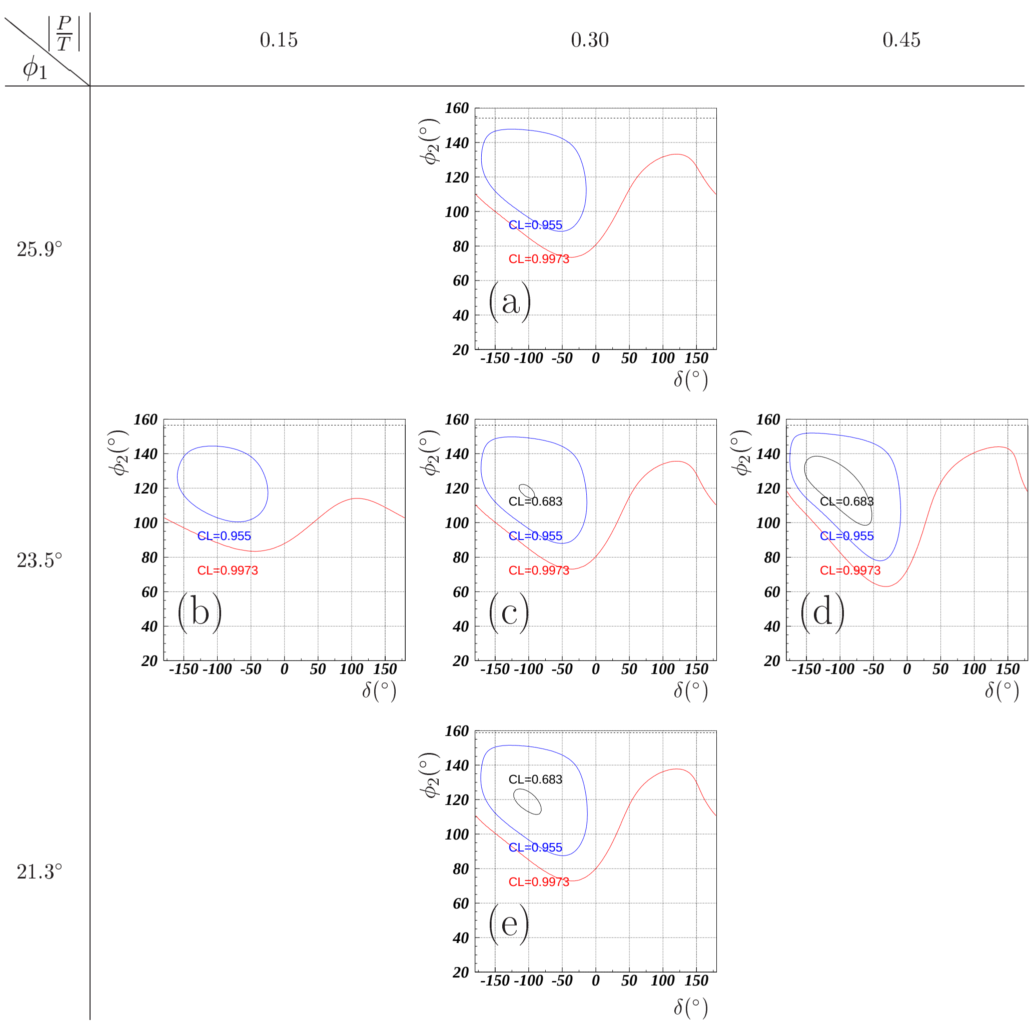

Figure 4: The regions for ϕ_2 and δ corresponding to the 68.3%, 95.5%, and 99.73% C.L. regions of $\mathcal{A}_{\pi\pi}$ and $\mathcal{S}_{\pi\pi}$ in Fig. 3 for (a) $\phi_1 = 25.9^\circ$, $|P/T|$=0.3, (b) $\phi_1 = 23.5^\circ$, $|P/T|$=0.15, (c) $\phi_1 = 23.5^\circ$, $|P/T|$=0.3, (d) $\phi_1 = 23.5^\circ$, $|P/T|$=0.45, and (e) $\phi_1 = 21.3^\circ$, $|P/T|$=0.3. The horizontal dashed lines correspond to $\phi_2 = 180^\circ - \phi_1$.